Jet Propulsion Laboratory
California Institute of Technology

2017 Spacecraft Thermal Control Workshop

Thermally Isolating Structures for Mars Surface Missions

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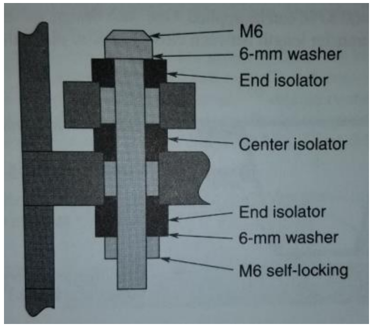
Common Types of Thermal Isolation

Less Volume

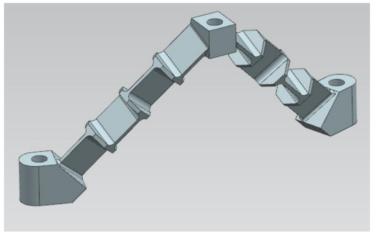
Better Performance

- G-10, FR-10, or Ceramic Washers
  - Low Volume, Worst Performance
  - Used when volume is at a premium and thermal performance is not critical
  - Less structurally efficient when paired with a bolt



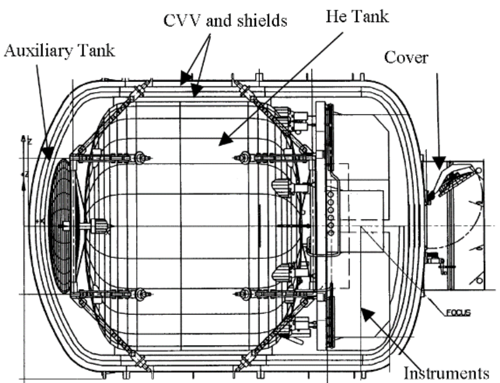
Washer Thermal Isolation [1]

- Bipod, Flexure, or Strut Structural Isolation
  - Moderate Volume, Thickness, and Performance
  - Deterministic structural and thermal design
  - Most commonly used on Martian surface



Ti Bipod

- Tension Band or Cable System
  - Large Volume, Best performance
  - All members are in tension
  - High structural efficiency
  - Often used in Cryogenics



FIRST/Plank Cryostat [2]

[1] Gilmore, D. (ed.), "Spacecraft Thermal Control Handbook," 2nd ed., The Aerospace Corporation, 2002.
[2] Collaudin, B., and Passvogel, T., "The FIRST/Plank Mission Cryogenic Systems – Current Status," Proc. SPIE Vol. 3356, pp. 1114-1126.

Thermal Isolating Materials

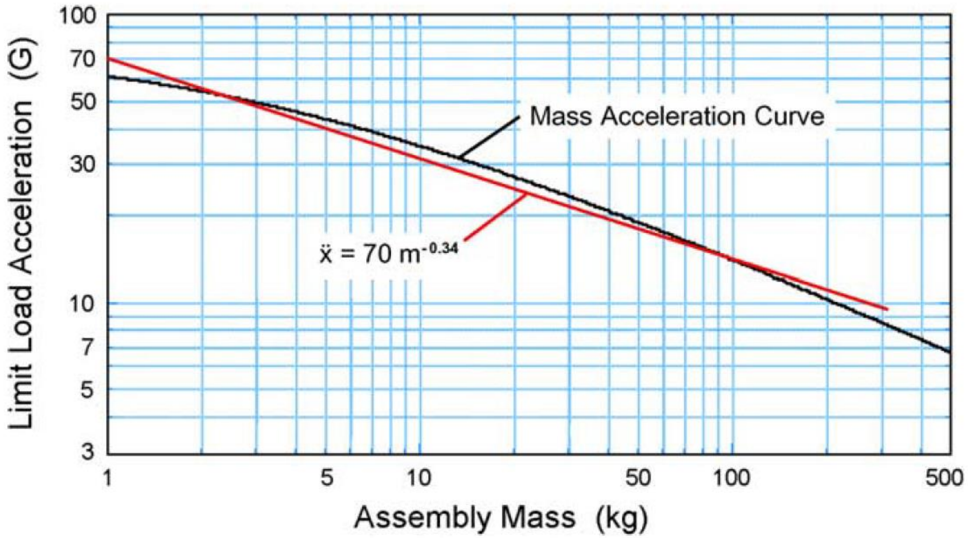
- Boron Epoxy and G-10 fiber reinforced polymer (FRP) composites perform better than Ti-6Al-4V, but are anisotropic and must account for creep / stress relaxation.

	Thermal Conductivity, k (W/m-K)	Yield Stress, σ_y (MPa)	Figure of Merit σ_y / k (MPa-m-K/W)
Boron-Epoxy FRP*	1.7 W/m-K [3]	1340 MPa (195 ksi) [3]	788
G-10 FRP*	0.9 W/m-K [4]	275 MPa (40 ksi) [4]	305
Ti-6Al-4V	7.3 W/m-K [1]	860 MPa (125 ksi) [5]	118
15-5 Stainless H900	16 W/m-K [6]	1030 MPa (150 ksi) [5]	64
Al-7075 T6	121 W/m-K [1]	480 MPa (70 ksi) [5]	4

* Note: Properties evaluated in the direction of the fibers.

[1] Gilmore, D. (ed.), “Spacecraft Thermal Control Handbook,” 2nd ed., The Aerospace Corporation, 2002.
[3] Chamis, D., “Design Properties of Randomly Reinforced Fiber Composites,” NASA Technical Note D-6696, 1972.
[4] G-10CR Materials Database, http://materialdatabase.magnet.fsu.edu/G10.htm, accessed 10/6/2014.
[5] Metallic Materials Properties Development and Standardization (MMPDS-05), FAA, April 2010.
[6] 15-5 PH Stainless Steel Product Data Sheet, AK Steel, http://www.aksteel.com/pdf/markets_products/stainless/precipitation/15-5_ph_data_sheet.pdf, accessed 11/9/2017.

Literature Review



Literature Recommended Equation [7]:

- $Q \approx \mathscr{A} \kappa m^{0.66} \Delta T$
  - Q = conductive heat flow (W)
  - $\mathscr{A}$ = empirical constant
    - Varies from 0.02 to 0.27 cm/Kg$^{0.66}$
  - κ = average thermal conductivity (W/cm-K)
  - m = mass (Kg)
  - ΔT = temperature difference (K)

- Curve Fit to Mass Acceleration Curve:
  - Acceleration, $\ddot{x} \propto m^{-0.34}$
- F = $\mathrm{m}\ddot{x}$
  - Force, $F \propto m^{0.66}$
- F = σA
  - Area, $A \propto m^{0.66}$
- G = kA/L
  - Conductance, $G \propto m^{0.66}$

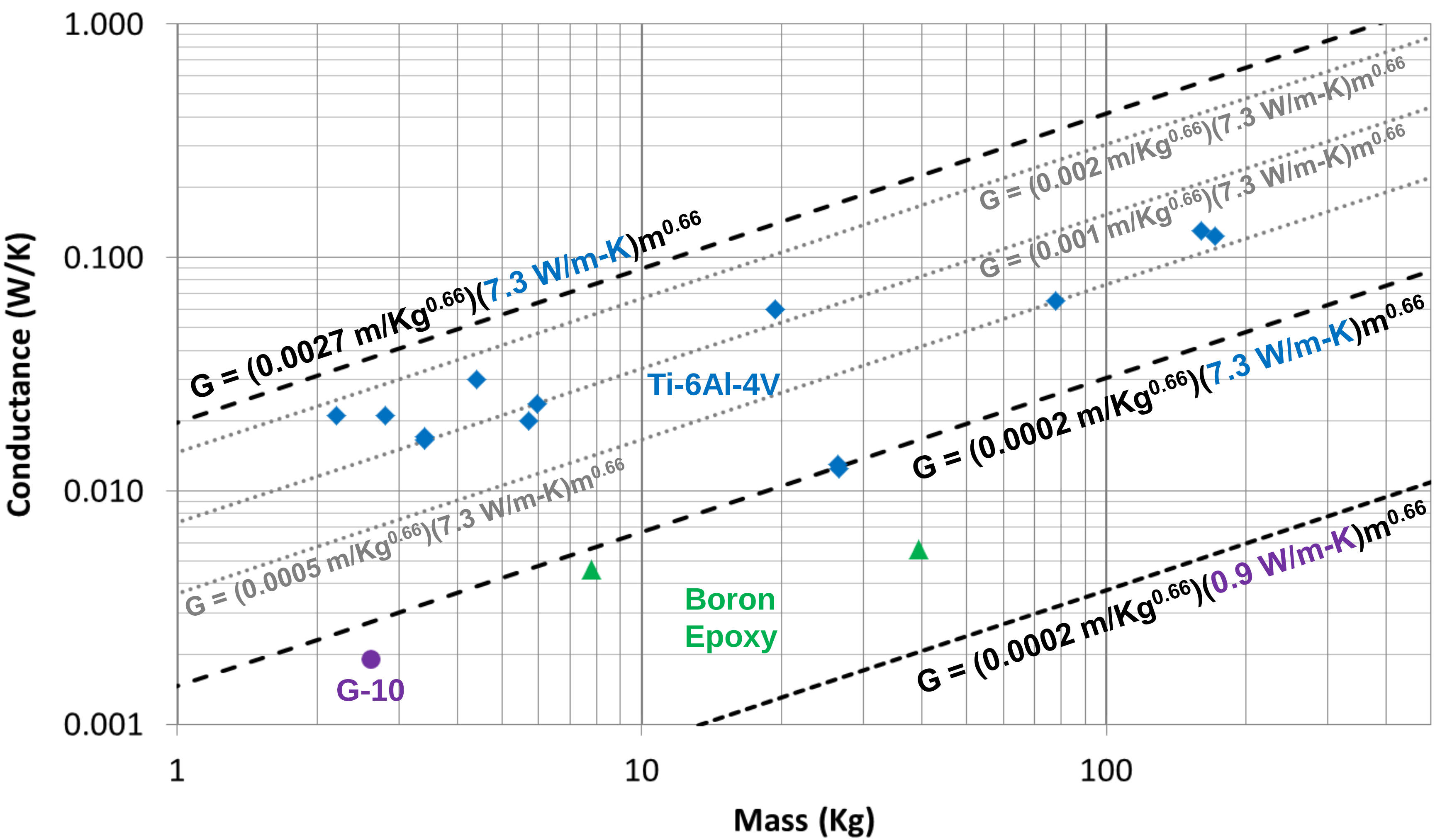
Simplified Metric Form:

- $G = \mathscr{A} k m^{0.66}$
  - $\mathscr{A}$ = empirical constant
    - varies from 0.0002 to 0.0027 m/Kg$^{0.66}$
  - G = conductance (W/K)
  - k = thermal conductivity (W/m-K)
  - m = mass (Kg)
- Very useful early in project lifecycle!

[7] Ross, R., "Estimation of thermal conduction loads for structural supports of cryogenic spacecraft assemblies," Cryogenics, Vol. 44, pp. 421 – 424.

MER, MSL & Mars 2020 Empirical Data

Thermal Isolation from the Mars Exploration Rovers (MER), Mars Science Lab (MSL) and Mars 2020 Rovers usually fall within the range predicted by G = $\mathscr{A}km^{0.66}$



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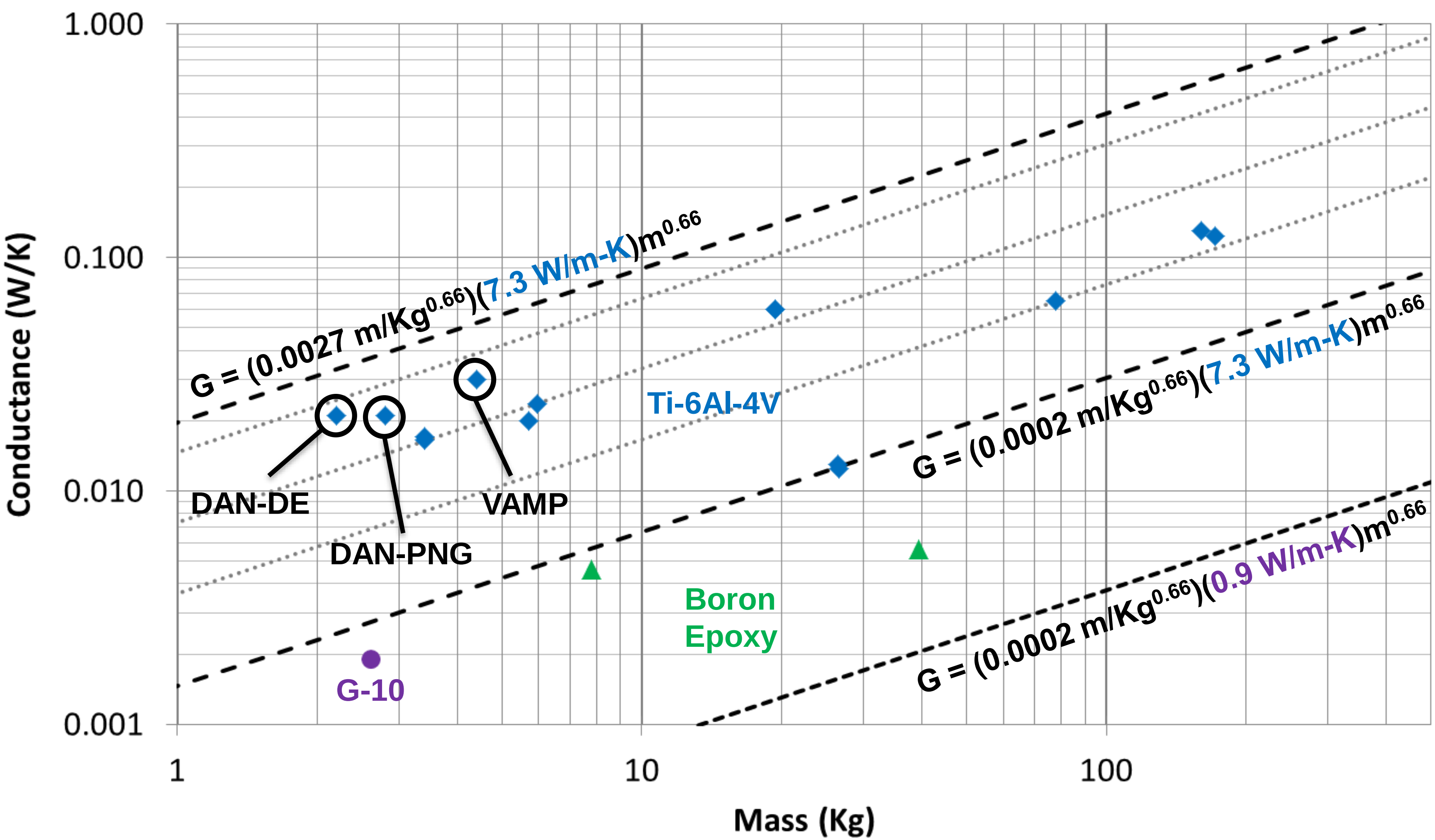


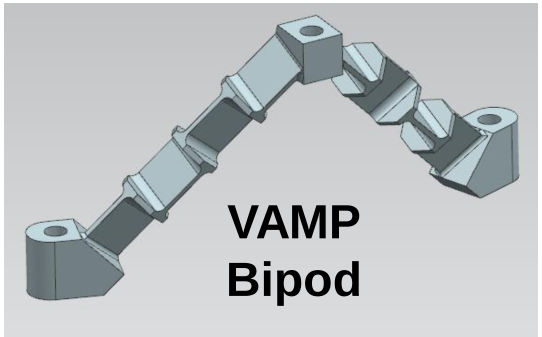
MSL DAN and Mars 2020 VAMP

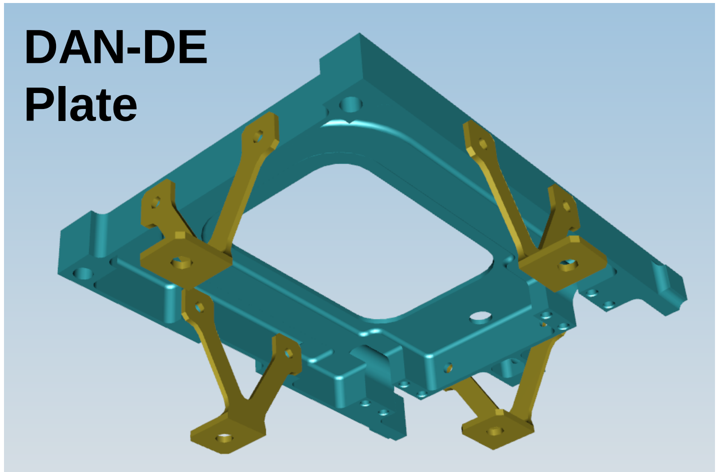
Mars 2020 Vertical Avionics Mounting Plates (VAMP)

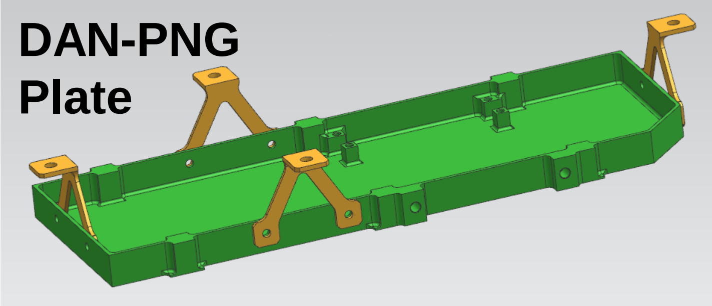
- Ti-6Al-4V Bipods
  - VAMP Mass = 4.4 Kg
  - Conductance = 0.030 W/K

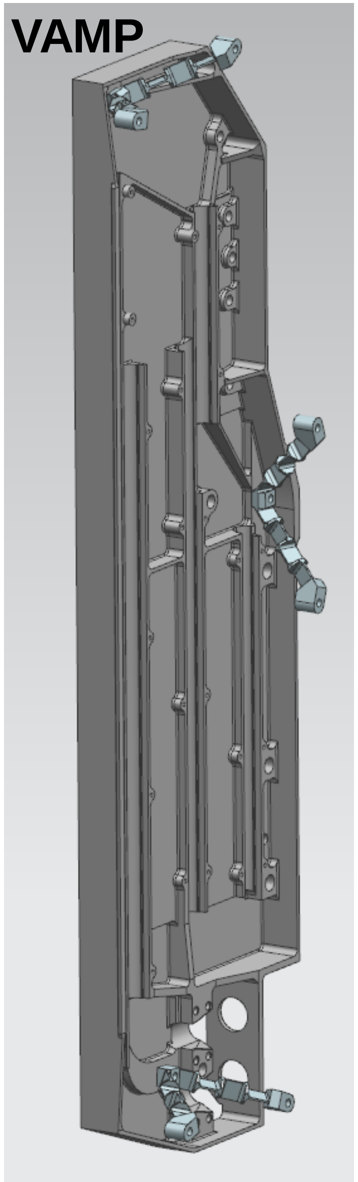
MSL Dynamic Albedo of Neutron (DAN) Plates

- DAN-DE (Detector Electronics)
  - Ti-6Al-4V Bipods
  - DAN-DE Mass = 2.2 Kg
  - Conductance = 0.021 W/K
- DAN-PNG (Pulse Neutron Generator)
  - Ti-6Al-4V Bipods
  - DAN-PNG Mass = 2.8 Kg
  - Conductance = 0.021 W/K









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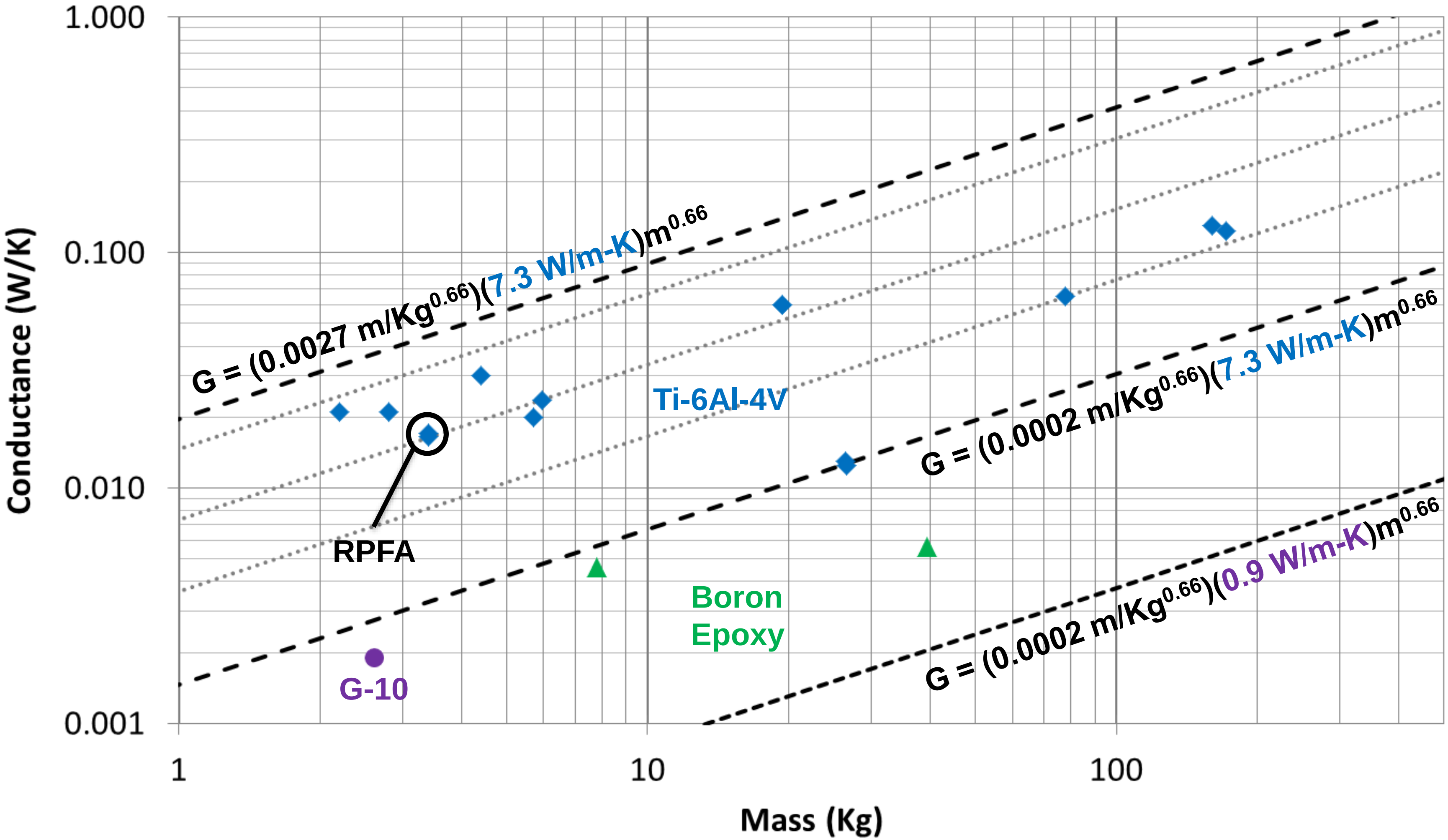

MSL and Mars 2020 RPFA

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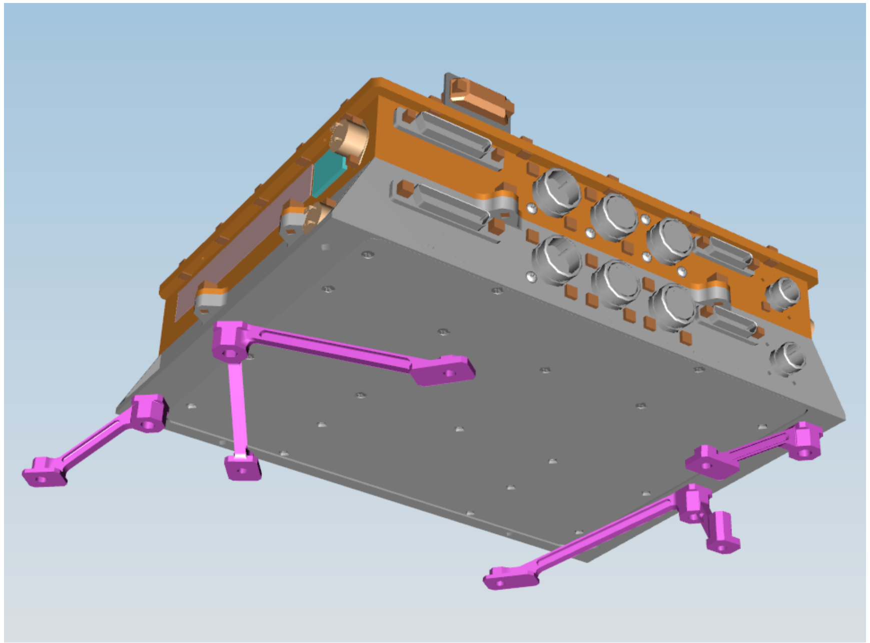
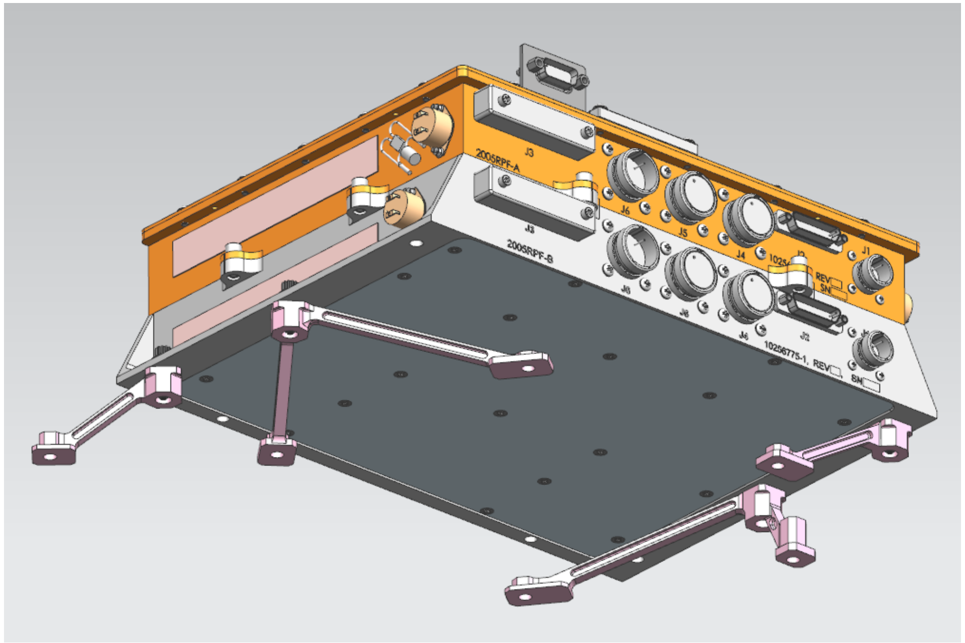
MSL RPFA
(Rover Pyro Firing Assembly)

- Ti-6Al-4V Bipods and Monopods
  - RPFA Mass = 3.4 Kg
  - Conductance = 0.017 W/K

Mars 2020 RPFA
(Rover Pyro Firing Assembly)

- Ti-6Al-4V Bipods and Monopods
  - RPFA Mass = 3.4 Kg
  - Conductance = 0.017 W/K





MER, MSL & Mars 2020 Empirical Data

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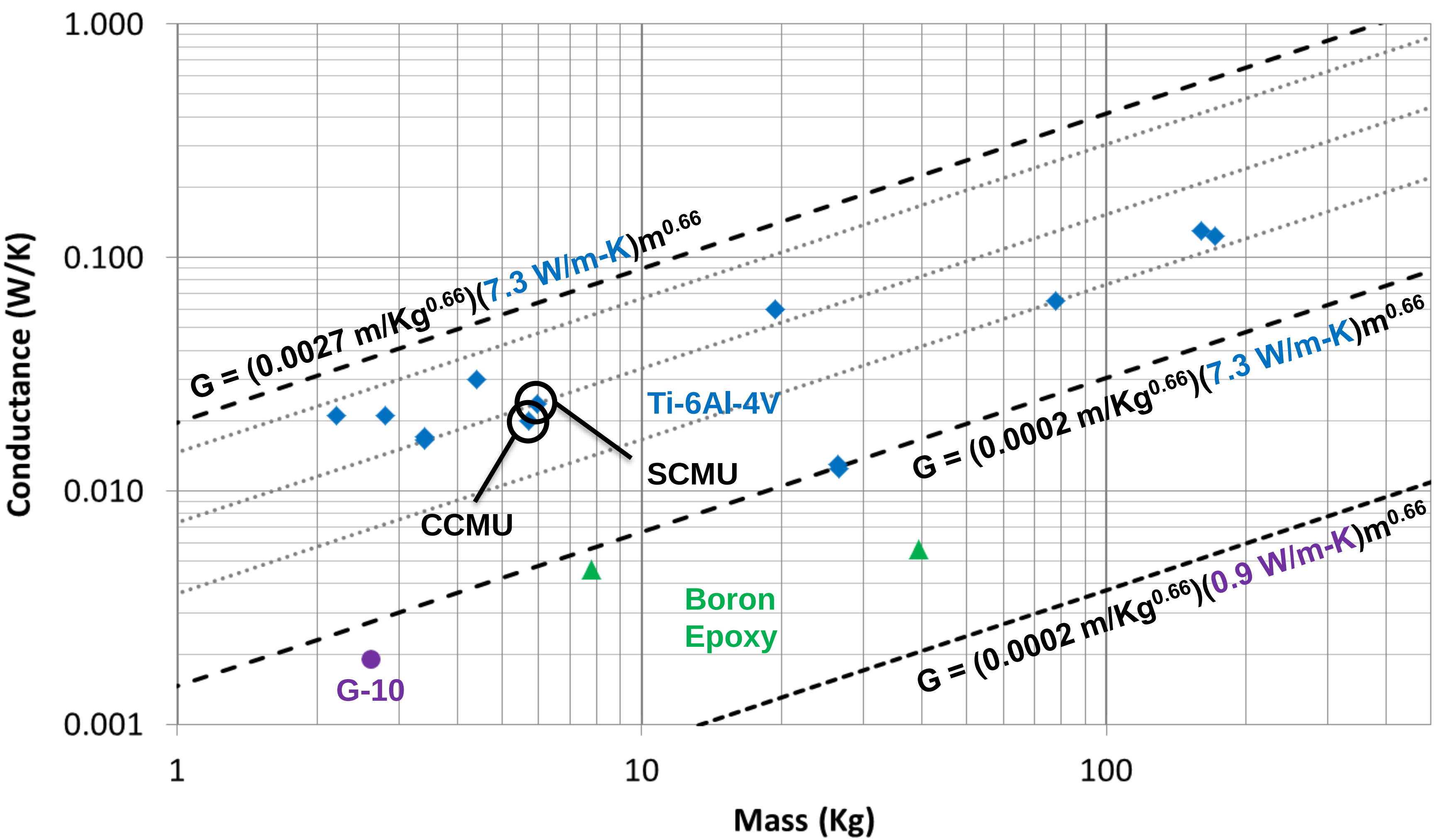


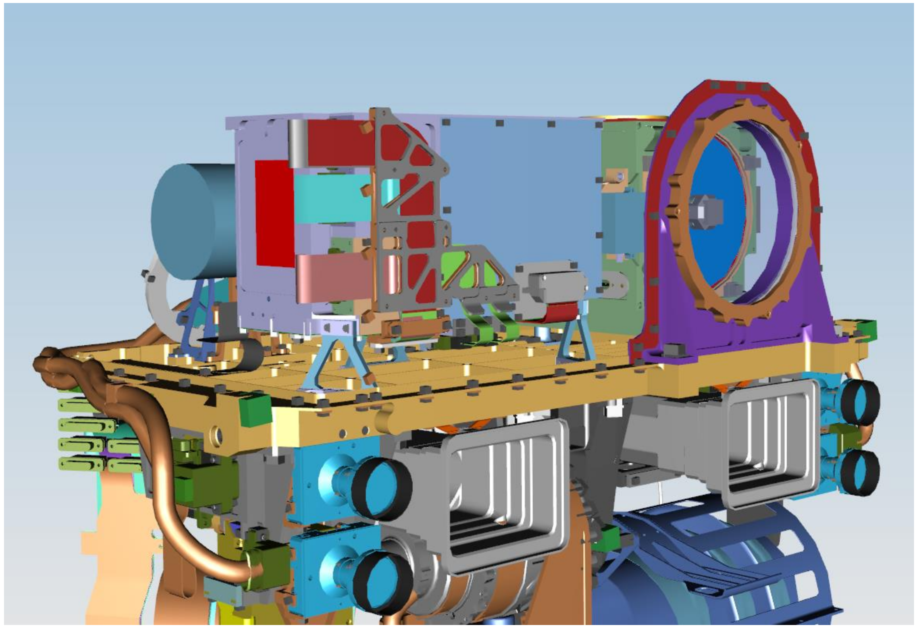
MSL and Mars 2020 Mast Instrument

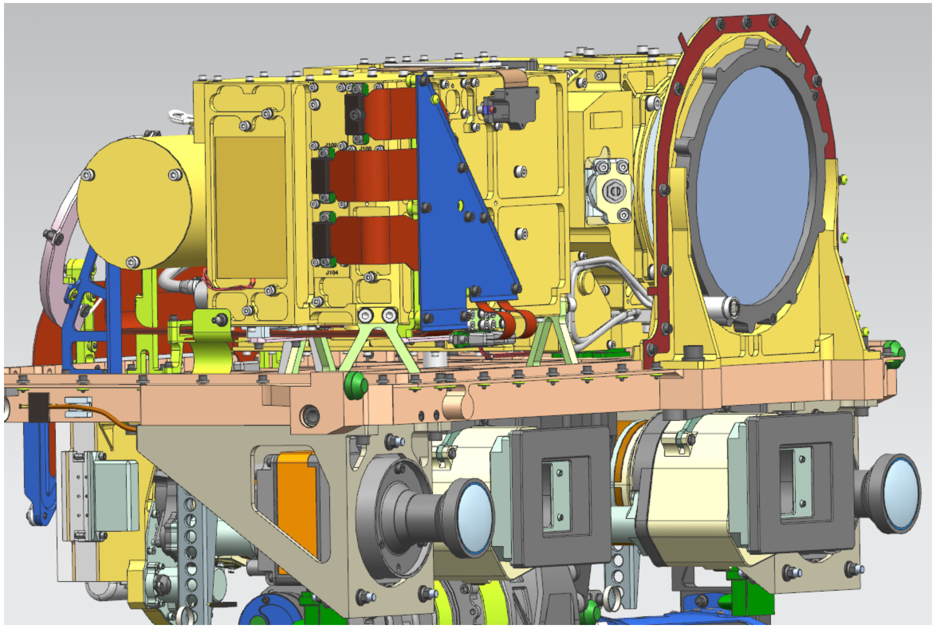
MSL CCMU (ChemCam Mast Unit)

- Ti-6Al-4V Bipods
  - CCMU Mass = 5.7 Kg
  - Conductance = 0.020 W/K

Mars 2020 SCMU (SuperCam Mast Unit)

- Ti-6Al-4V Bipods
  - SCMU Mass = 5.9 Kg
  - Conductance = 0.024 W/K





MER, MSL & Mars 2020 Empirical Data

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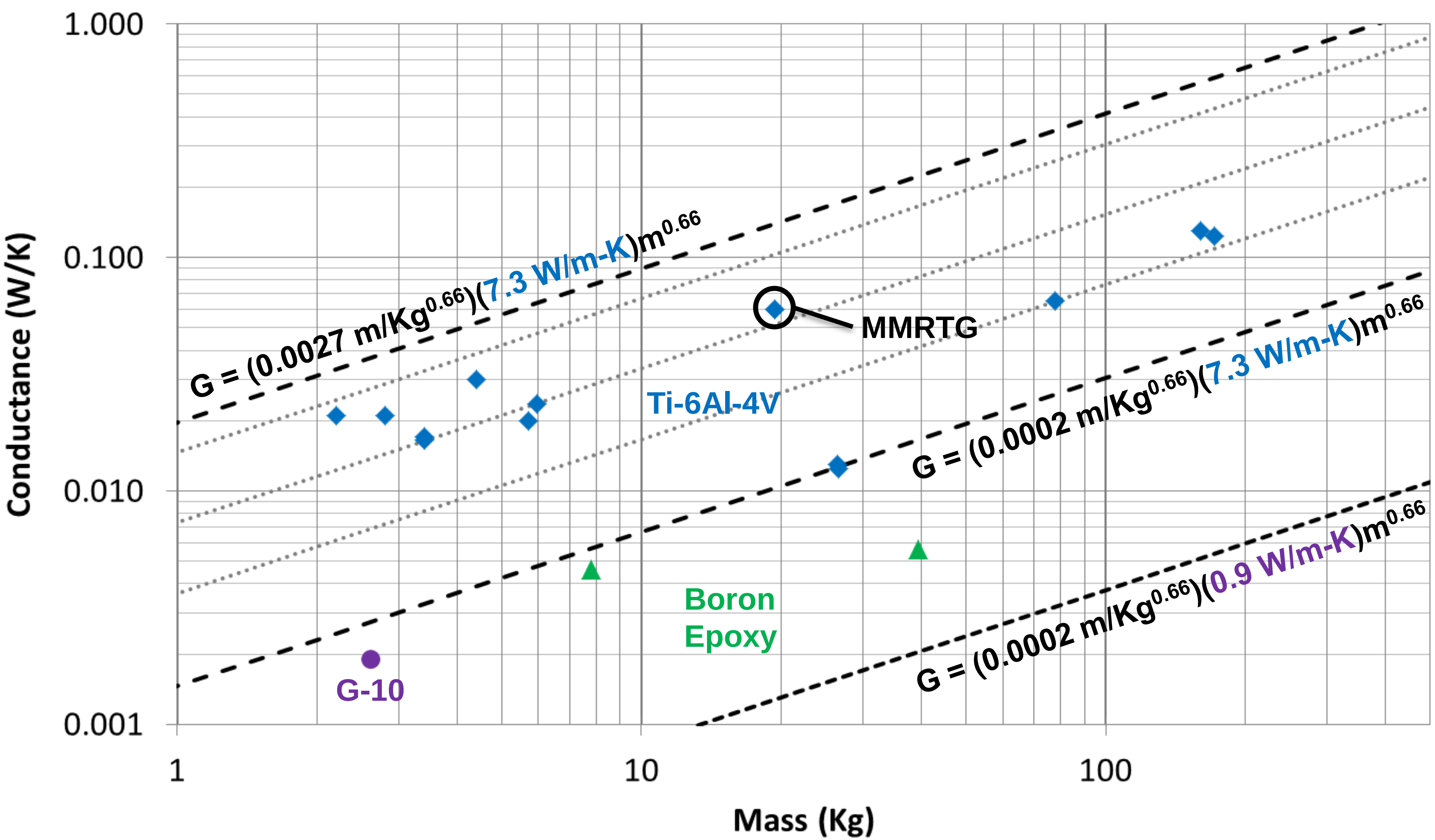

MSL and Mars 2020 MMRTG

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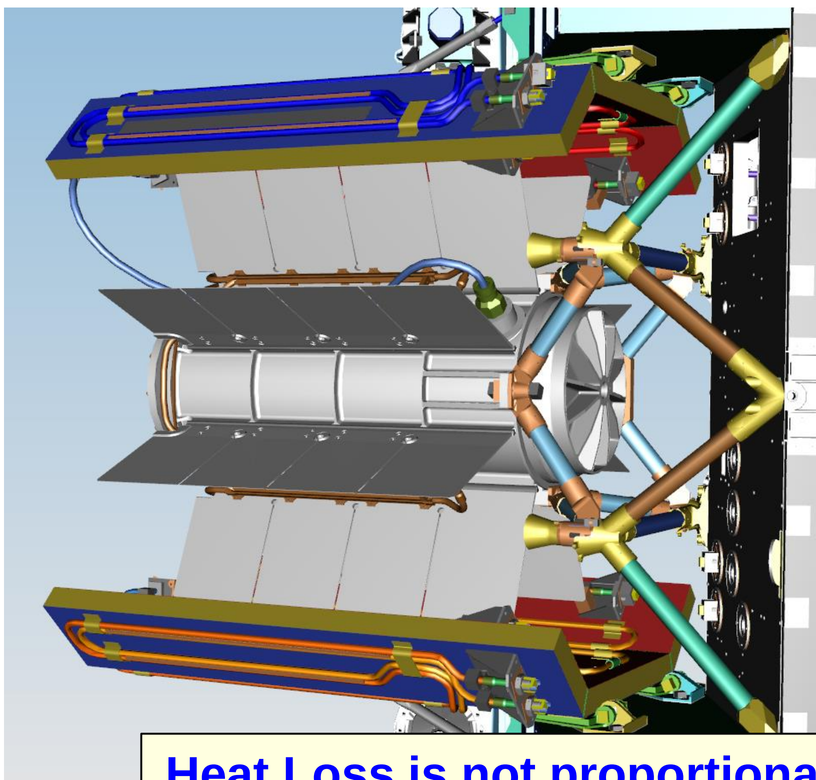
MMRTG = Multi Mission Radioisotope Thermoelectric Generator

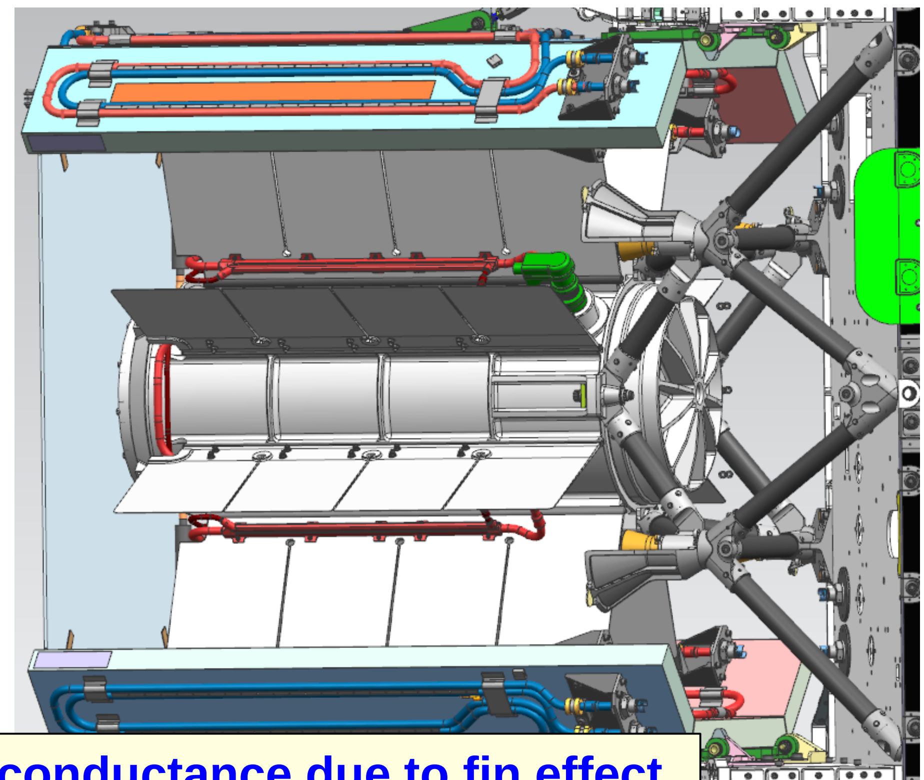
MSL MMRTG

- Ti-3Al-2.5V Struts
  - MMRTG Mass = 19.4 Kg
  - Conductance = 0.09 W/K

Mars 2020 MMRTG

- Ti-3Al-2.5V Struts
  - MMRTG Mass = 19.4 Kg
  - Conductance = 0.09 W/K





Heat Loss is not proportional to conductance due to fin effect.

MER, MSL & Mars 2020 Empirical Data

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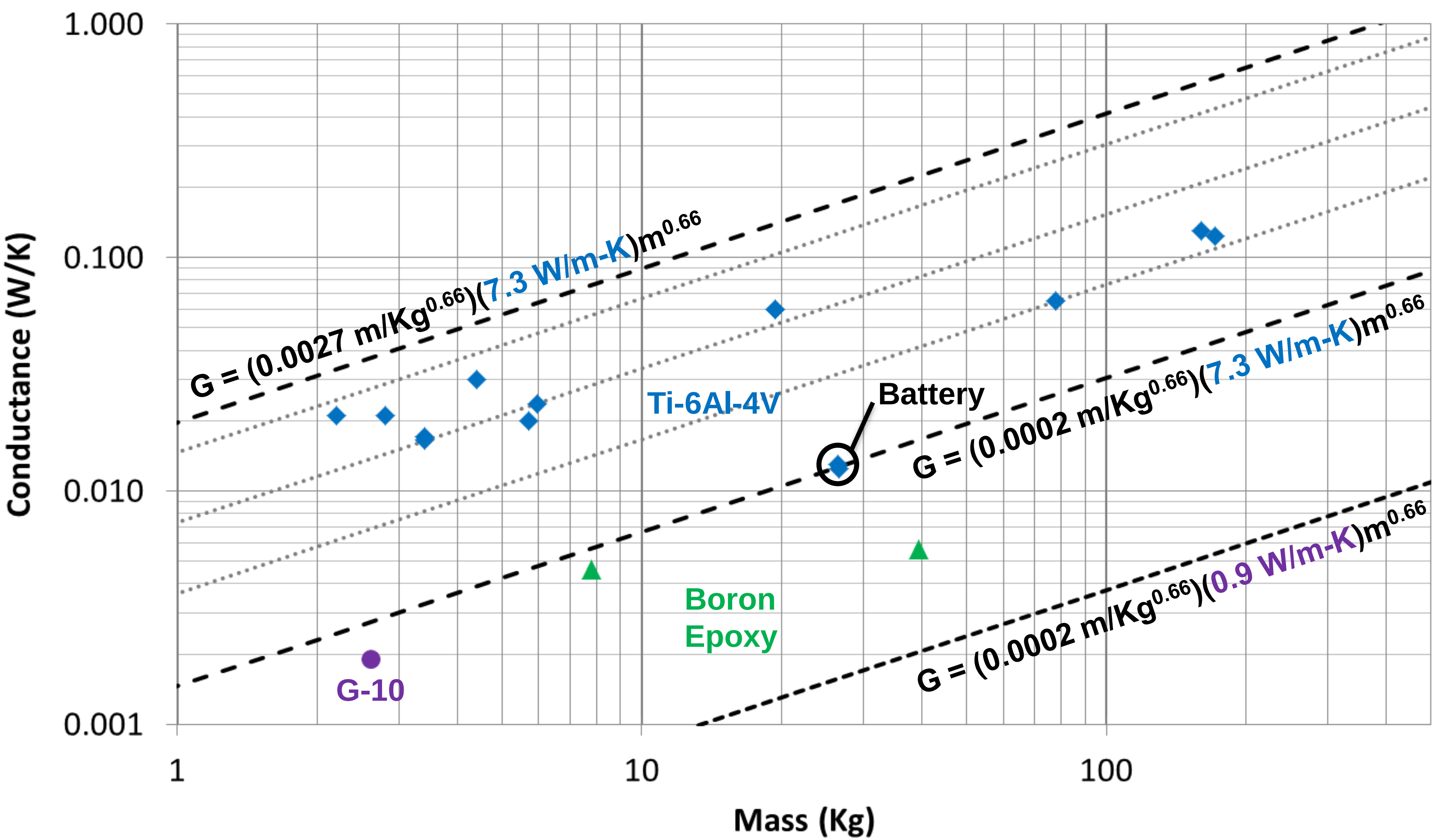
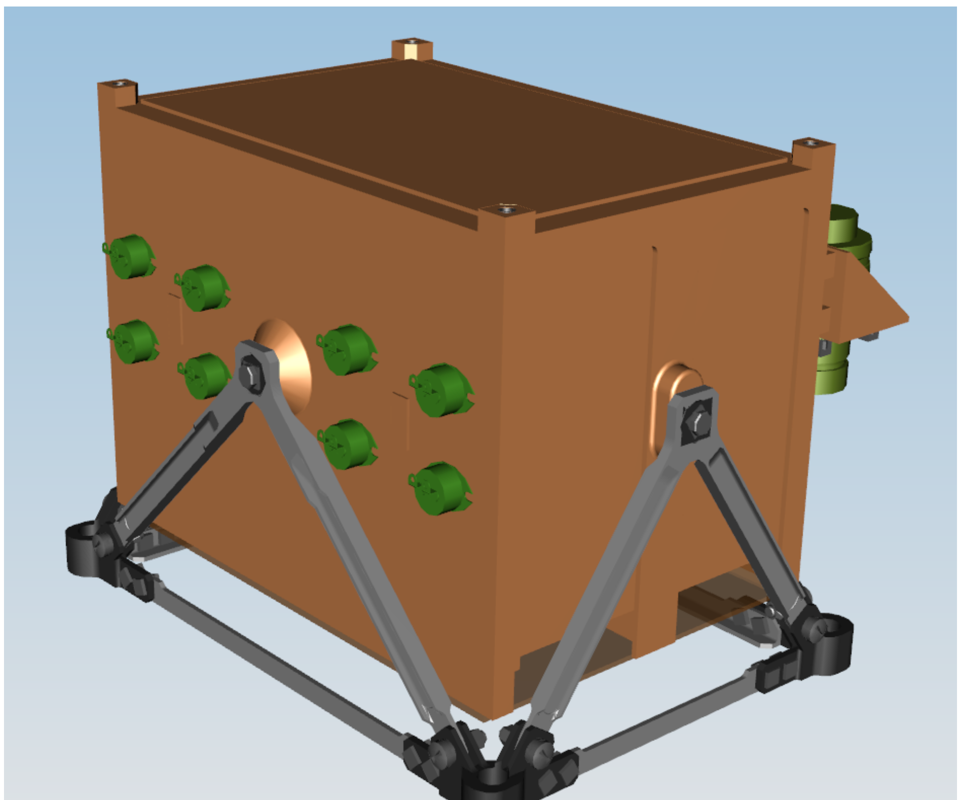


MSL and Mars 2020 Battery

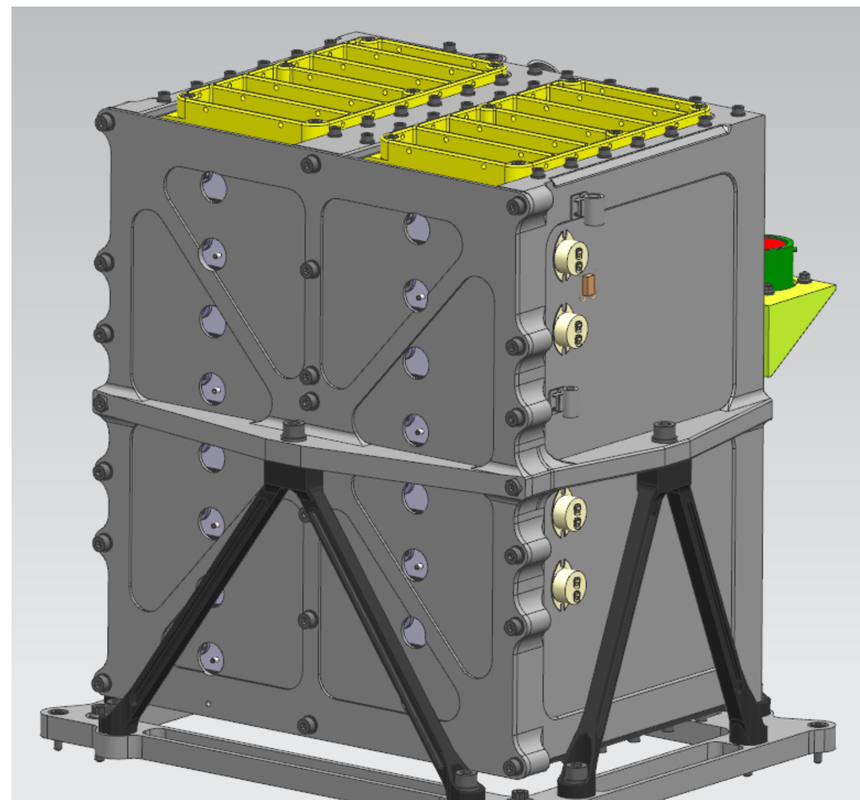
MSL

- Ti-6Al-4V Bipods
  - Battery Mass = 26.4 Kg
  - Conductance = 0.013 W/K



Mars 2020

- Ti-6Al-4V Bipods
  - Battery Mass = 26.6 Kg
  - Conductance = 0.013 W/K



Performance can be improved by using more volume resources

MER, MSL & Mars 2020 Empirical Data

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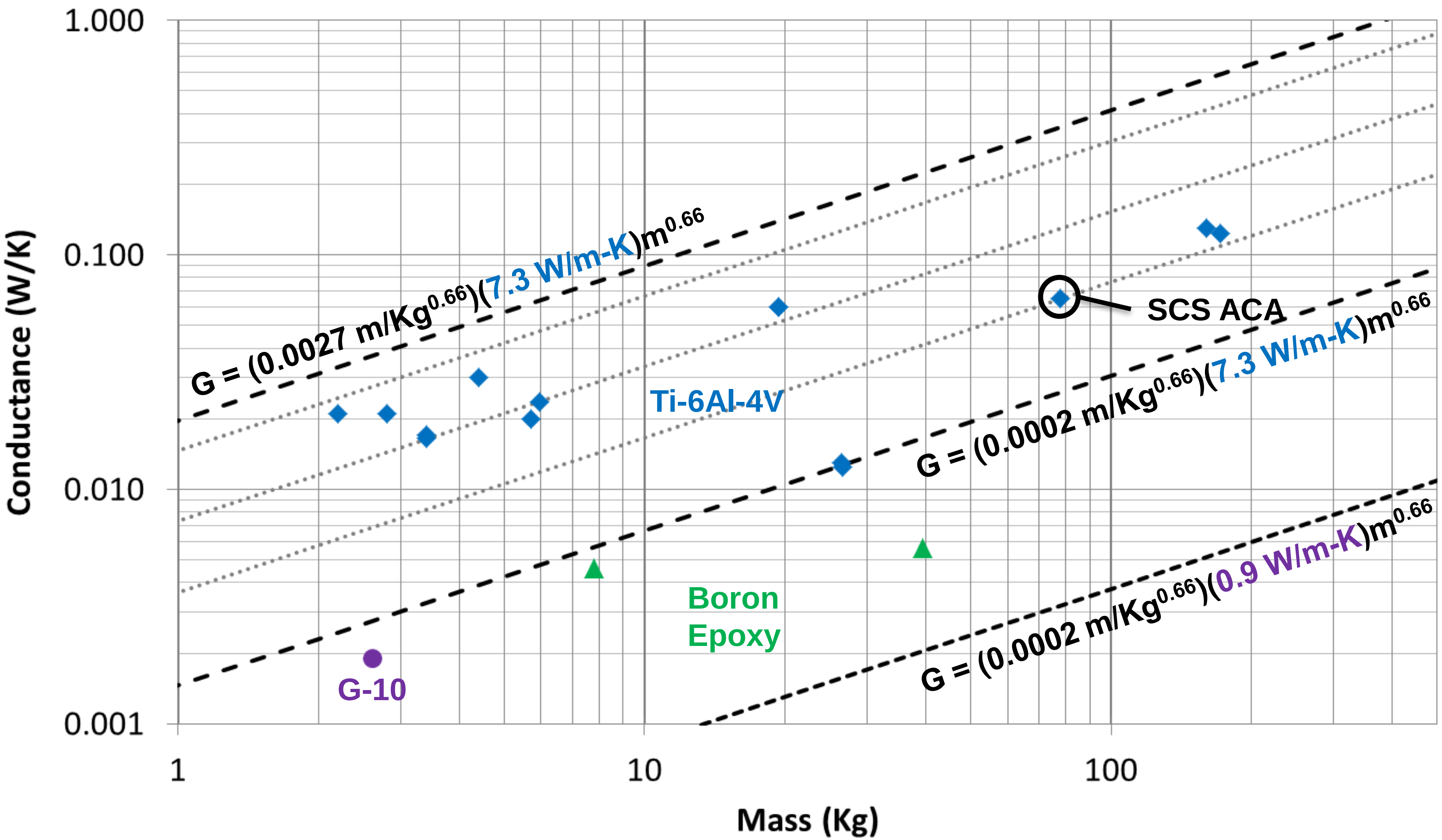
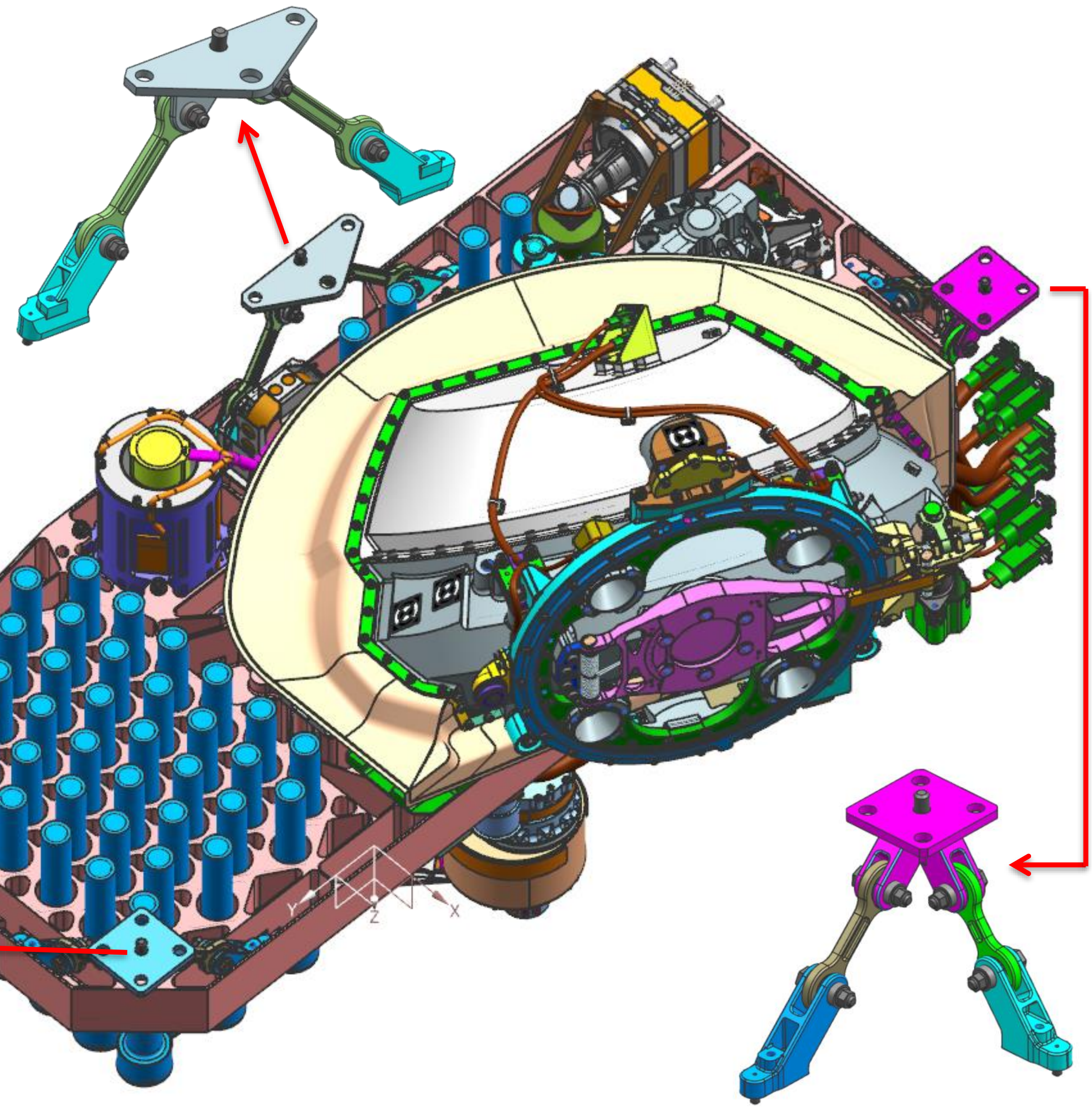
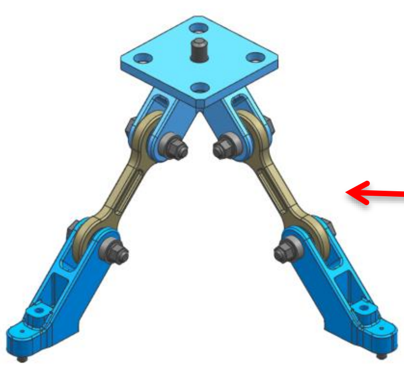


Mars 2020 SCS ACA

Mars 2020 SCS ACA
(Sample Caching System Adaptive Caching Assembly)

- Ti-6Al-4V Ball and Clevis Bipods
  - ACA Mass = 77.6 Kg
  - Conductance = 0.065 W/K





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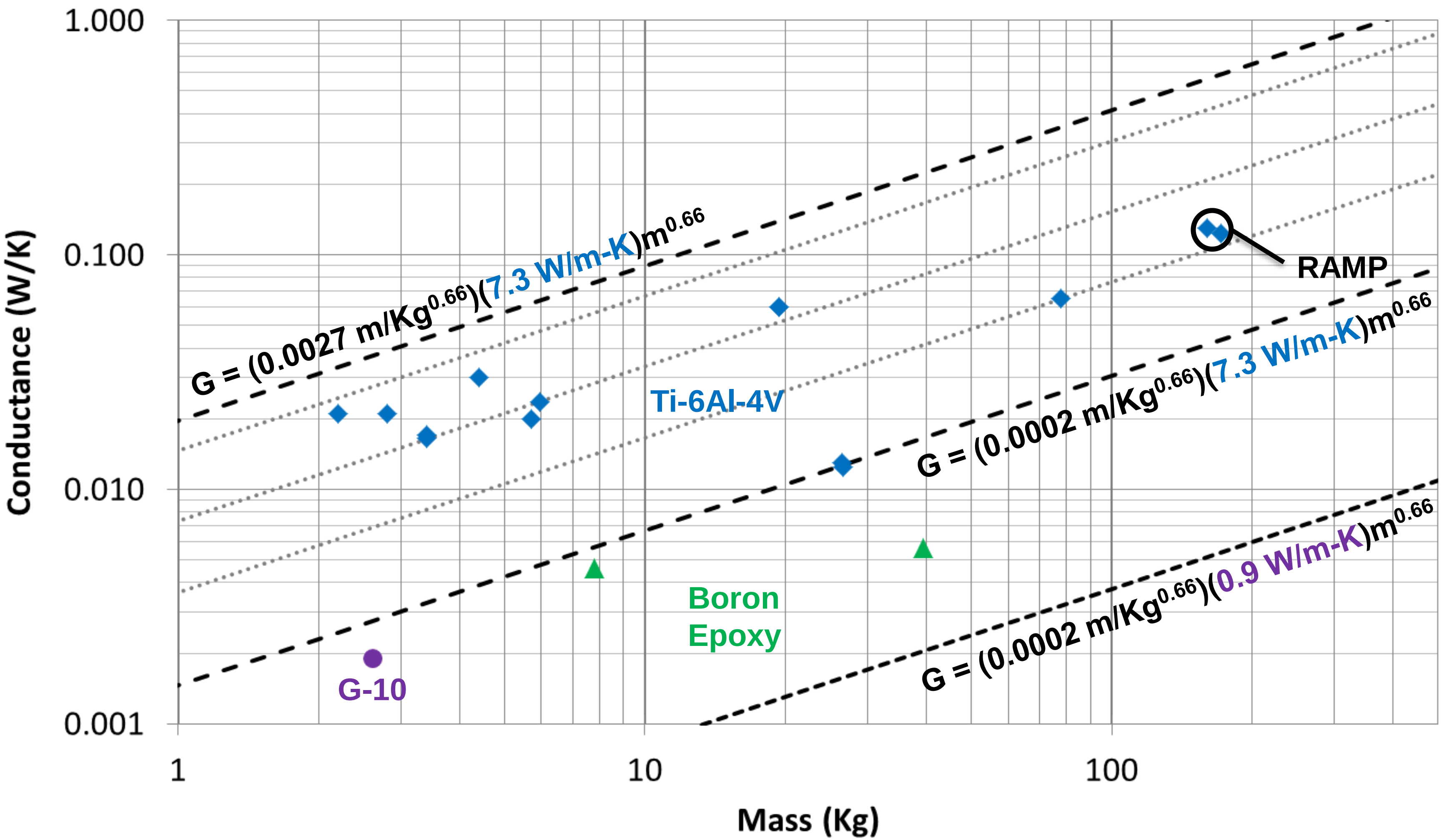

MSL and Mars 2020 RAMP

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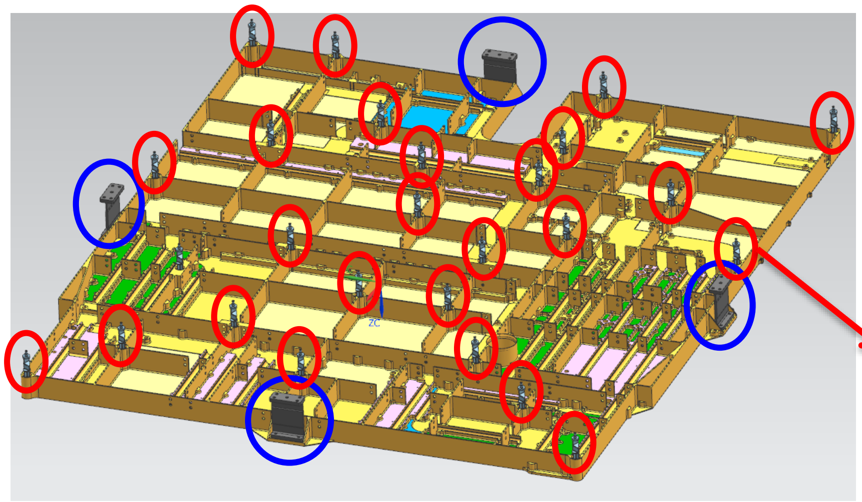
RAMP = Rover Avionics Mounting Panel

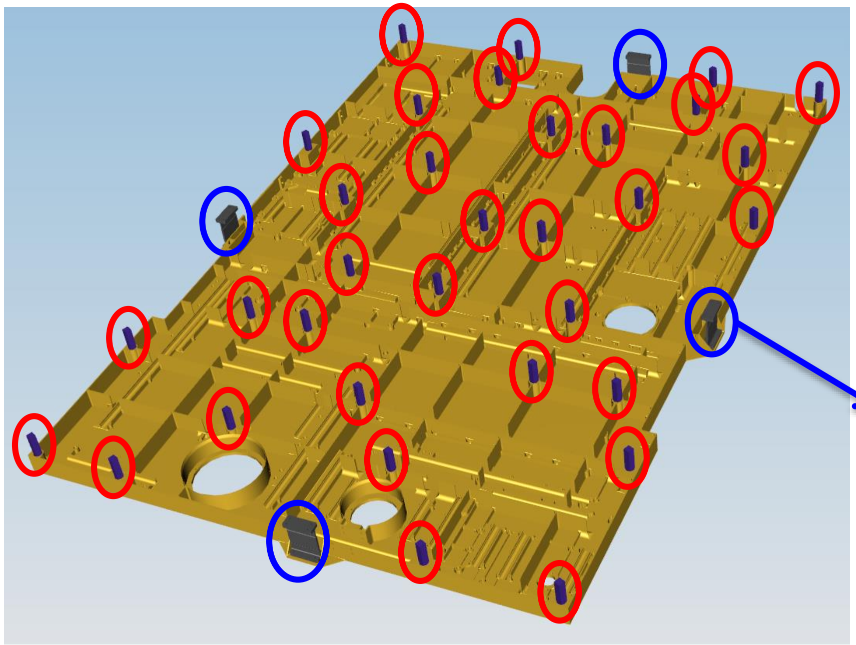
Mars 2020

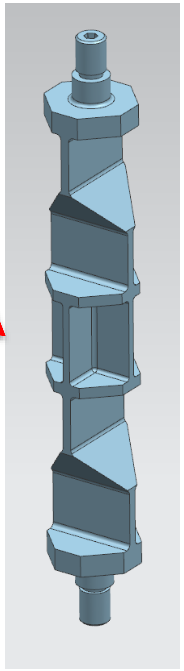
- Ti-6Al-4V Flexures "Bed of Nails"
  - RAMP Mass = 171 Kg
  - Conductance = 0.012 W/K

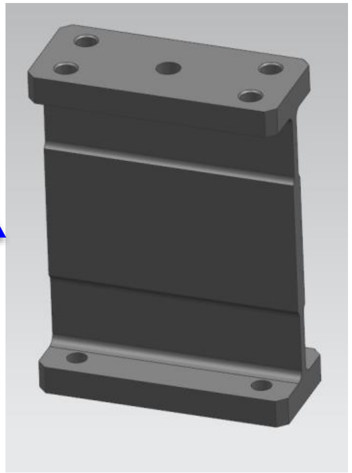
MSL

- Ti-6Al-4V Flexures "Bed of Nails"
  - RAMP Mass = 160 Kg
  - Conductance = 0.013 W/K









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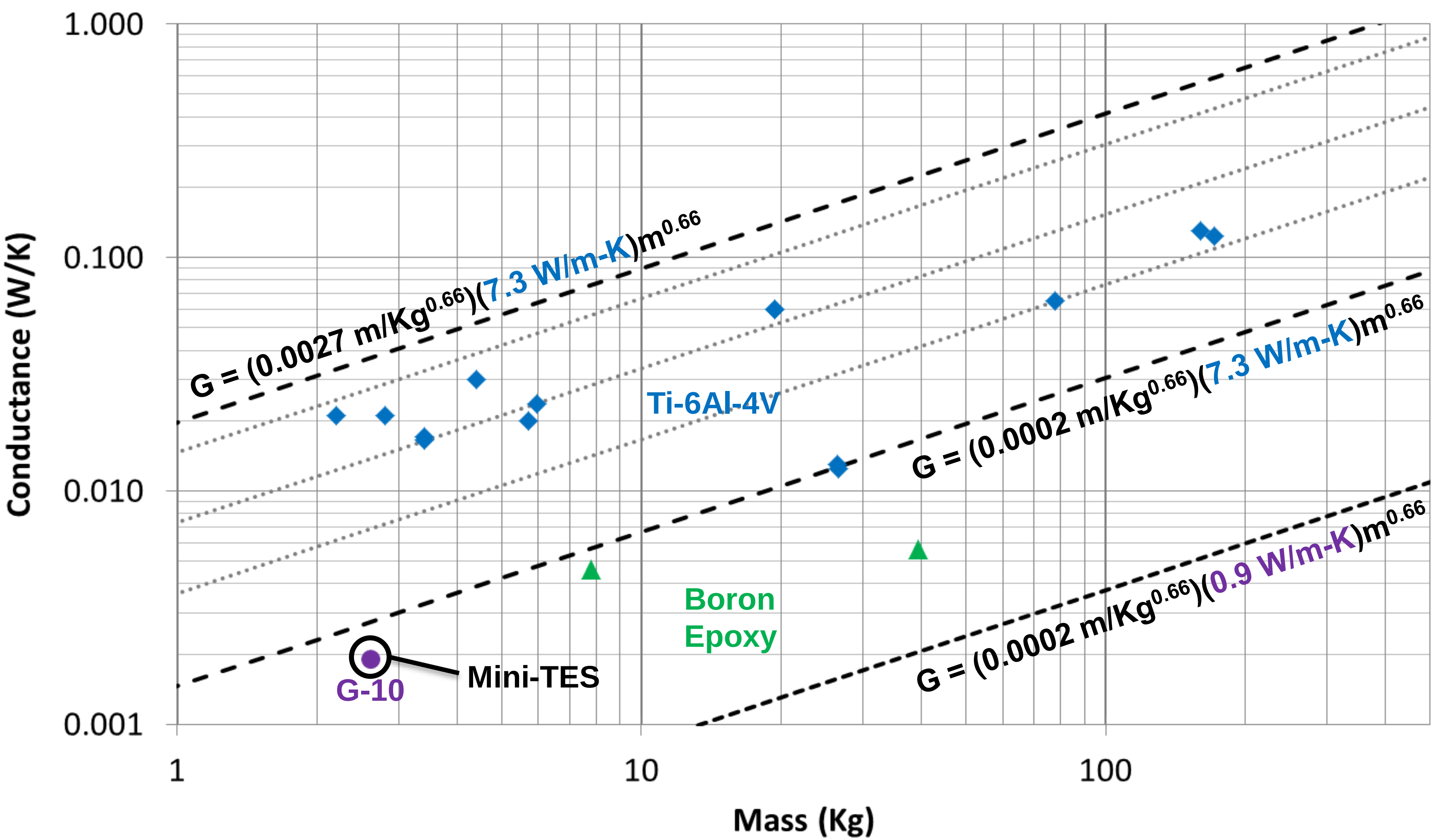
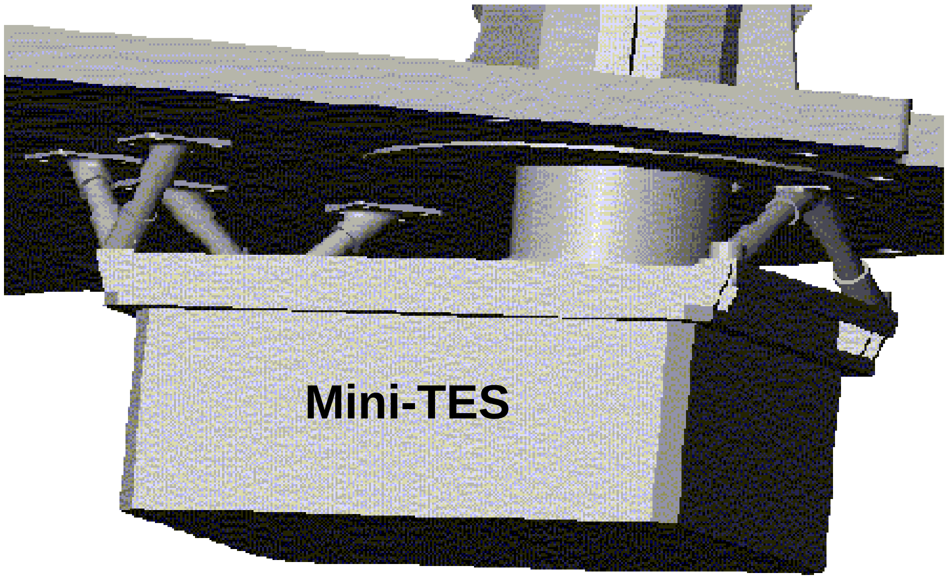


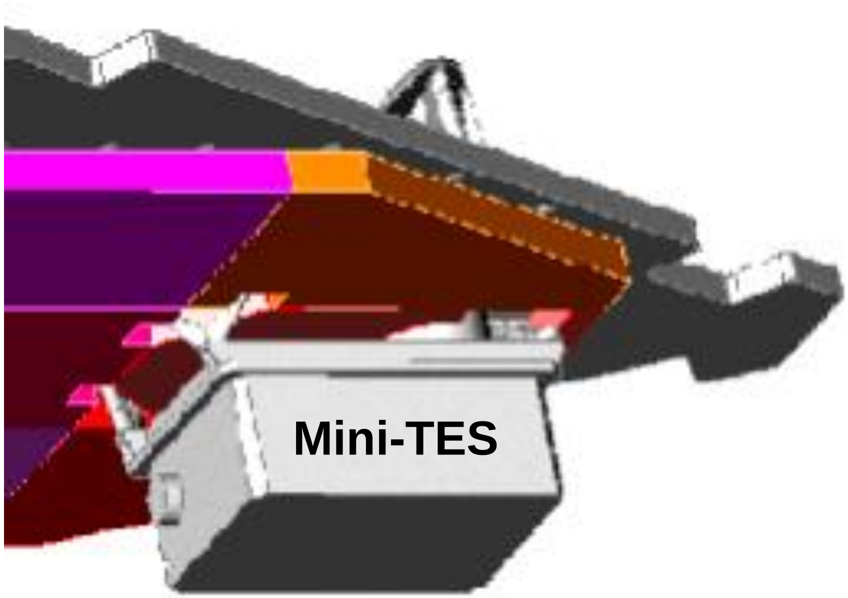
MER Mini-TES

- G-10 Struts with Ti-6Al-4V Fittings
  - Mini-TES Mass = 2.6 Kg
  - Conductance = 0.002 W/K

View without Aerogel Insulation



View with Aerogel Insulation



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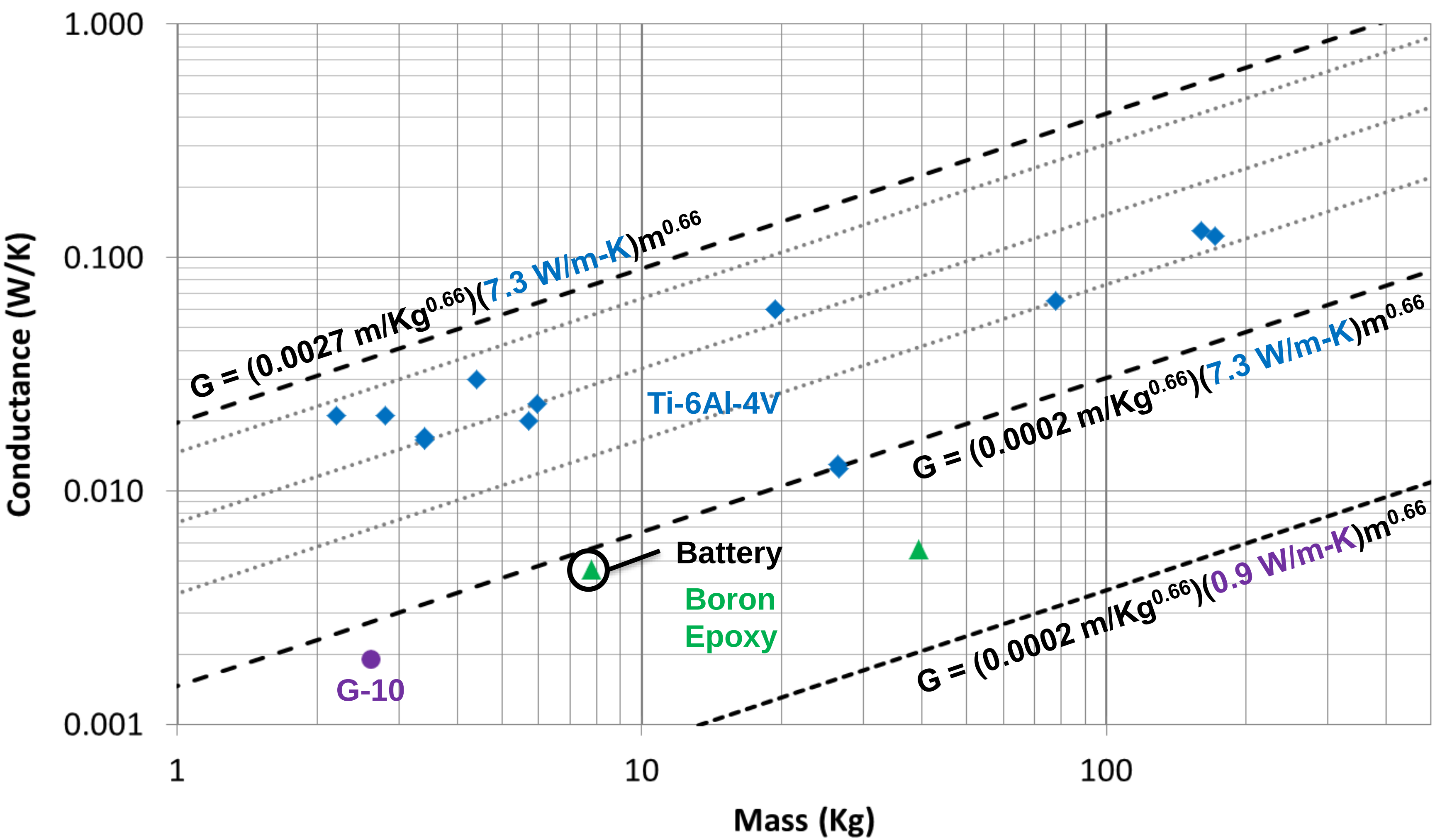
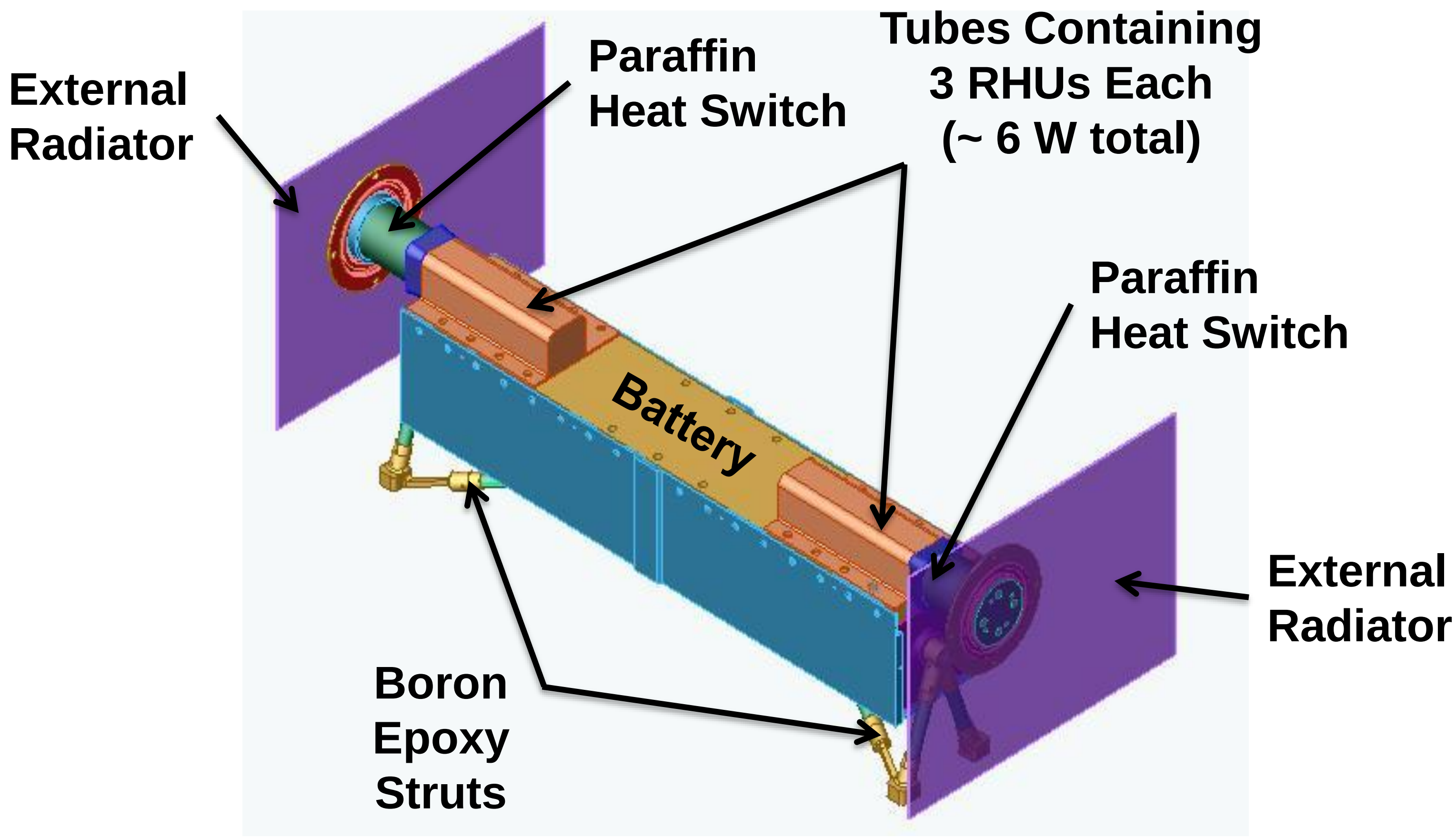


MER Battery

- Boron Epoxy Struts with Ti-6Al-4V Fittings
  - Battery Mass = 7.8 Kg
  - Conductance = 0.005 W/K



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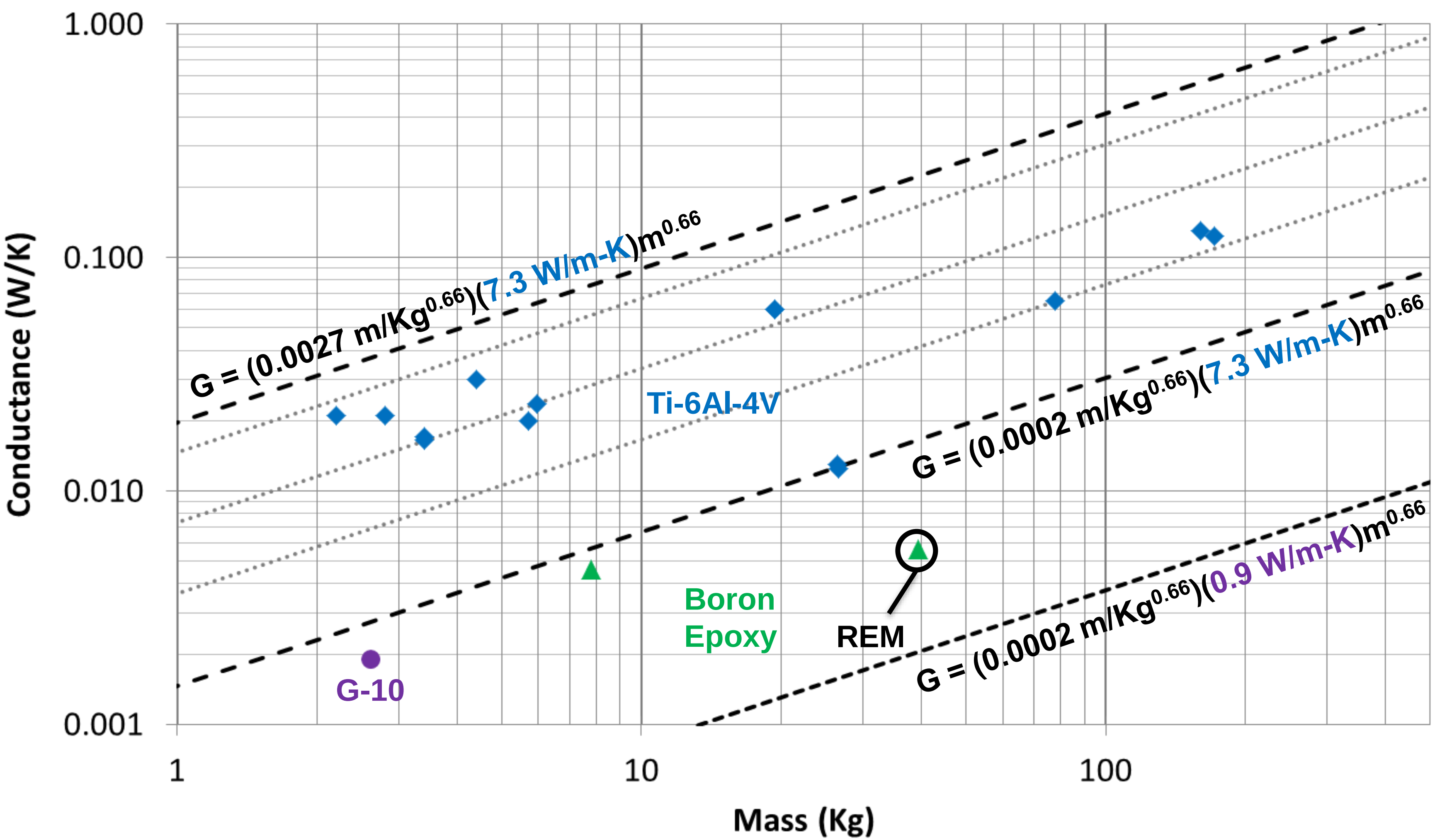
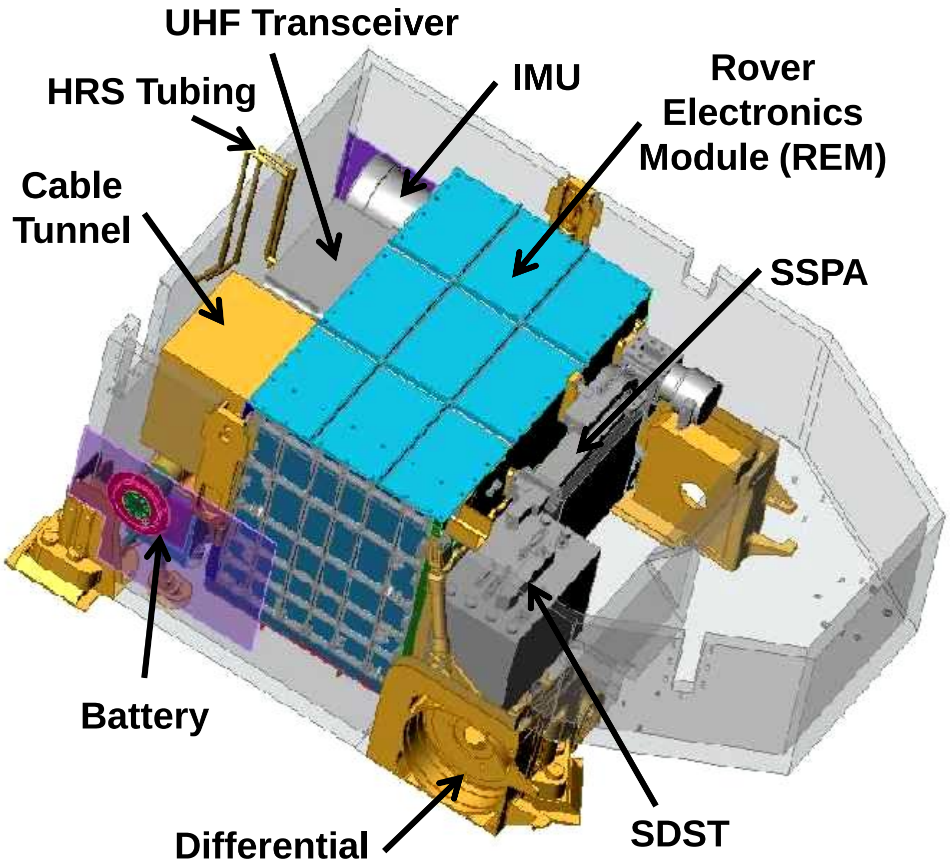
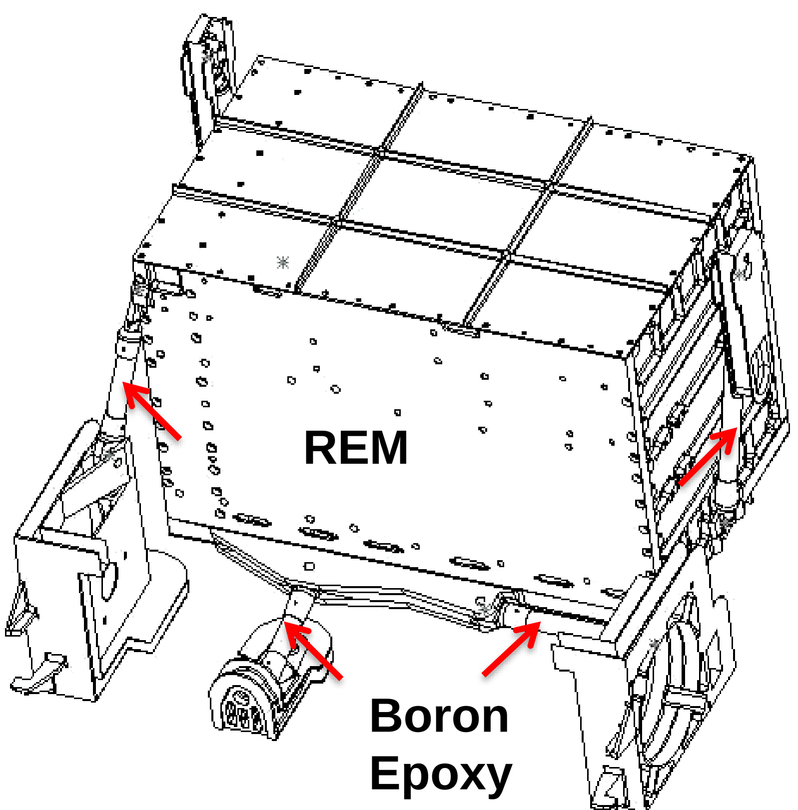


MER Rover Electronics Module (REM)

- Boron Epoxy Struts with Ti-6Al-4V Fittings
  - REM Mass = 39.4 Kg
  - Conductance = 0.006 W/K





Don't Forget Cabling Heat Losses!

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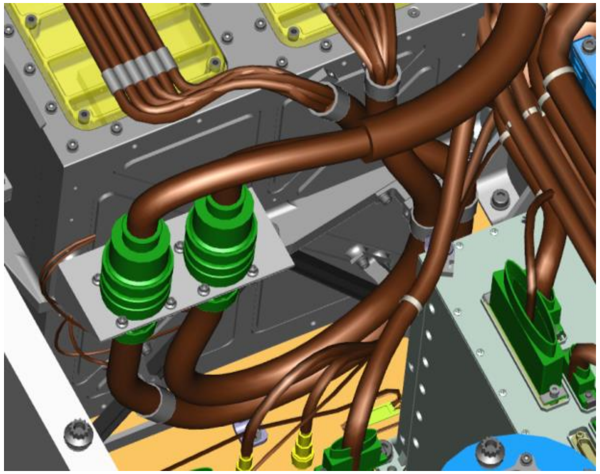
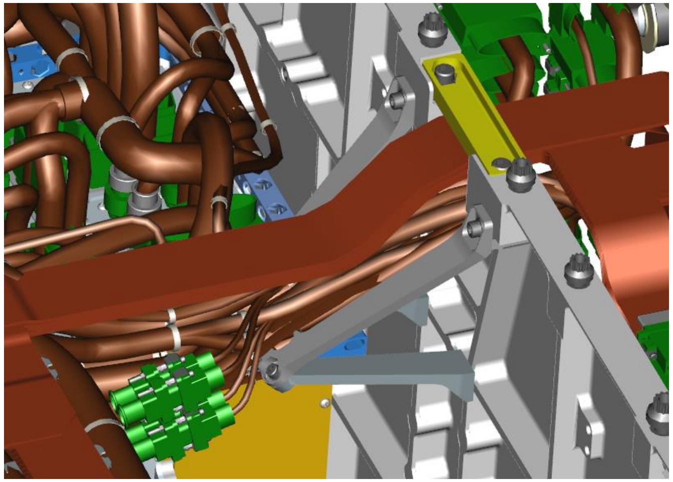
	Cable Type	Min Length	Max Copper Cross Section	Insulation	Approx. G
MER REM (Rover Electronics Module)	Flex Cables	0.5 m	148 mm^2 (0.23 in^2)	Foam "cable tunnel"	0.12 W/K
MSL and Mars 2020 RAMP (Rover Avionics Mounting Panel)	Round Wire and Flex Cables	0.25 m	542 mm^2 (0.84 in^2)	CO2 "gas gap" and Ti-6Al-4V Cable Supports	0.83 W/K
MSL and Mars 2020 Battery	Round Wire	0.25 m	47 mm^2 (0.07 in^2)	CO2 "gas gap" and Bracket	0.07 W/K



Mars 2020 Battery Cables



Example of Mars 2020 RAMP Cable "Mouse Hole"

Flex cables have a much lower copper cross section due to their reduced EMI shielding copper cross section, which can be significant for round wire.

Conclusions

- Titanium Bipods, Flexures, and Struts are often used for thermal isolation due to their good performance, isotropic properties, elastic behavior, and relatively low cost.
  - G-10 and Boron Epoxy composites are sometimes used when performance is critical, but have several downsides.

- Empirical correlations can be used to estimate the conductance of thermally isolating structures early in a project life cycle.
  - Adapted from cryogenics.
  - Account for variation in thermal conductivity, but not strength.
  - Do not account for radiative or convective fin effects.
  - For Ti-6Al-4V, $G = (0.001\ m/Kg^{0.66})(7.3\ W/m\text{-}K)m^{0.66}$ is a reasonable “target”.
  - Does not include heat losses due to cabling.

- The amount of volume and engineering effort that goes into designing low conductance structures has a significant effect on the final conductance of a given structure.

References

1. Gilmore, D. (ed.), “Spacecraft Thermal Control Handbook,” 2nd ed., The Aerospace Corporation, 2002.
2. Collaudin, B., and Passvogel, T., “The FIRST/Plank Mission Cryogenic Systems – Current Status,” Proc. SPIE Vol. 3356, pp. 1114-1126.
3. Chamis, D., “Design Properties of Randomly Reinforced Fiber Composites,” NASA Technical Note D-6696, 1972.
4. G-10CR Materials Database, http://materialdatabase.magnet.fsu.edu/G10.htm, accessed 10/6/2014.
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6. 15-5 PH Stainless Steel Product Data Sheet, AK Steel, http://www.aksteel.com/pdf/markets_products/stainless/precipitation/15-5_ph_data_sheet.pdf, accessed 11/9/2017.
7. Ross, R., “Estimation of thermal conduction loads for structural supports of cryogenic spacecraft assemblies,” Cryogenics, Vol. 44, pp. 421 – 424.